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**CLIMATIC MODULATION OF SEISMICITY
IN THE ALPINE-HIMALAYAN MOUNTAIN RANGE**

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Abstract

The influence of strain field variations associated with seasonal and longer term climatic phenomena on earthquake occurrence is investigated. Two regions (Himalaya and Alps), characterized by present day mountain building and relevant glaciers retreat, as well as by sufficiently long earthquake catalogues, are suitable for the analysis. Secular variations of permanent glaciers dimensions, which are naturally grossly correlated with long-term average surface atmosphere temperature changes, as well as seasonal snow load, cause crustal deformations that modulate seismicity.

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Introduction

Tectonic forces responsible for mountain building must overcome, among others, gravity force. Heki (2003) evidences the competing effects of tectonic forces and the load due to snow and shows that snow load, along the western flank of the backbone range of the Japanese Islands, causes seasonal crustal deformation, perturbs the interseismic strain buildup, and may seasonally influence the seismicity in Japan. Intraplate earthquakes in northeastern Japan occur on reverse faults, striking parallel with the snow-covered zone, while in central and southwestern Japan, they occur on strike-slip faults striking either parallel with or perpendicular to the snow cover. The snow load enhances compression at these faults, reducing the Coulomb failure stress by a few kPa, a value large enough to modulate the tectonic stress buildup of a few tens of kPa/yr. Inland earthquakes with magnitude $M \geq 7.0$, in regions covered with snow in winter, tend to occur more in spring and summer than in autumn and winter, while those in the snow-free regions do not show such variation. Although the statistical significance of this seasonal correlation is not strong, due to the limited time span of available observations (and hence a low number of past earthquakes), it suggests that the spring thaw enhances seismicity beneath the snow cover.

Indeed, as we will show later, the same correlation can be evidenced when analyzing the seismicity in the continent-continent collision areas of Himalaya and Alps, even if the main stress field there is much more complex than in ocean-continent collisions, like Japan.

On account of the fact that ice is about three times denser than snow and of the glacier shrinkage reported in the past century we look for effects of variations of glaciers extension, naturally associated with average global surface atmosphere temperature variations, on the seismicity of mountain ranges over period of times of the centuries. The areas that can be reliably investigated for this purpose are in the Northern hemisphere, namely the grossly E-W trending mountain ranges belonging to similar climatic zones, Alps and Himalaya, where are available reliable: (a) earthquake catalogues, at least since 1100 to present (see Table 1), (b) estimates of sizeable variations of permanent glacier size, and (c) estimates of average surface atmosphere temperature variations over a sufficiently long time period (Esper et al., 2002; Hansen et al., 2002; Jones and Mann, 2004 and references therein).

In the Southern hemisphere, the main mountain range (Andes) is essentially striking N-S, crosses very different climatic zones and the size variation of the permanent glacier reported is scattered and of minor entity (Barletta, 2007; Dyurgerov and Meier, 2005; GLIMS Glacier Database; World Glacier Inventory (WGI); R-HydroNET). These facts, along with the scarcity of estimates of the average surface temperature variation in the Southern hemisphere, do not warrant any quantitative study of the Andes, although a qualitative analysis of the area does not contradict the following evidences supplied by Alps and Himalaya.

Data analysis

A number of earthquake data sources have been considered and are listed in Table 1, while the source of average surface atmosphere temperature data is Esper et al. (2002). The purpose of the analysis is twofold: (a) to validate the presence of a seasonal effect, i.e. that the spring thaw enhances seismicity beneath the snow cover and (b) that a similar phenomenon, but on very different time scale, can be seen in connection with the shrinkage of permanent glaciers.

Table 1. Earthquake data sources considered in the analysis. Historical information from different regional sources has been cross-checked and integrated. Global data sets are used both for the analysis of seismicity in the Northern hemisphere, as well as to integrate and update information from regional catalogues.

Region	Time interval	Data source	References
Global	1900-2008	Global Hypocenters' Data Base cd-rom and its updates	NEIC/USGS (1989); Healy et al. (1992); Shebalin (1992, 1997)
	1900-2001	Centennial catalogue	Engdahl and Villaseñor (2002)
Himalaya	25 dC - 2001	Earthquake catalogue of India and surroundings	Parvez et al. (2002) and references therein
	2150 bC - 1995	Global Seismicity Catalog cd-rom, 2150 B.C. to 1995	NOAA National Geophysical Data Center (1996)
	=	Relevant publications	Feldl and Bilham (2006); Kumar et al. (2006); Lave' et al. (2005); Bilham and Ambraseys (2005); Pandey and Molnar (1988)
Alps	217 bC - 2001	Parametric catalogue of Italian Earthquakes (CPTI04)	Gasparini et al. (2004)
	342 bC - 1990	Historical Earthquake Catalogues: Central and southeastern Europe	Leydecker, G. (1991)
Apennines	217 bC - 2001	CPTI04	Gasparini et al. (2004)

a) Seasonal effect

The analysis of the seasonal effect is performed considering only earthquakes within the crust, as suggested by the theoretical computations of Heki (2003), and with a minimum magnitude threshold, variable from region to region, but corresponding to a number of events $N \geq 10$. Two measures of seismicity are considered, namely the number of events (N) with magnitude above a certain threshold (equal or greater than the magnitude completeness threshold of the existing catalogues) and the normalized strain (Σ) released by these events. Σ is computed based on Benioff strain release (Benioff, 1951) S_i , computed for each earthquake i with magnitude M_i , and normalized to the strain S_{\min} of the minimum magnitude M_{\min} considered for the analysis, that is:

$$\Sigma = \sum_i \frac{S_i}{S_{\min}} = \sum_i 10^{d(M_i - M_{\min})/2} \quad d = \text{const} \quad (1)$$

where for the constant d we use the value $d=1.5$ given by Gutenberg and Richter (1956).

The earthquakes have been naturally grouped accordingly to the four seasons: winter (WI), spring (SP), summer (SU), autumn (AU).

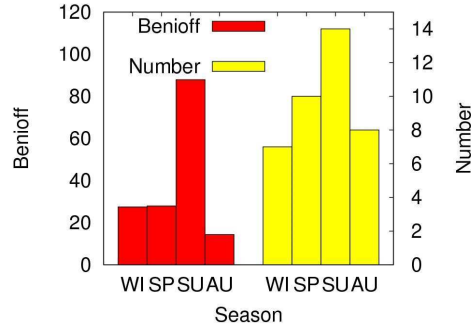


Fig. 1. Histograms of Σ and N for the crustal events with $M \geq 7.0$ which occurred in the period 1850-2008 in the Himalaya region.

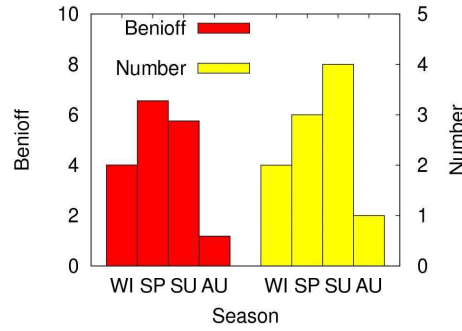


Fig. 2. Histograms of Σ and N for the crustal events with $M \geq 5.8$ which occurred in the period 1850-2008 in the Alps.

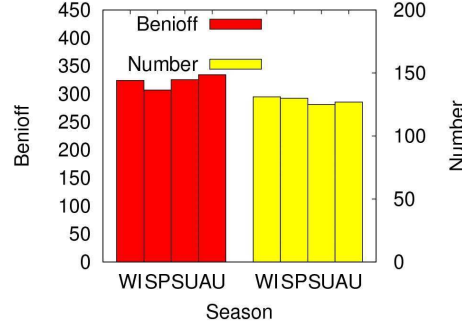


Fig. 3a. Histograms of Σ and N for crustal events with $M \geq 7.0$ which occurred in the period 1900-2008 in the Northern hemisphere (if Alpine and Himalayan events are removed the flat shape of the histograms remains unchanged).

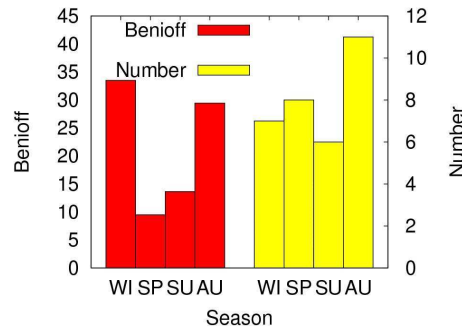


Fig. 3b. As in fig. 3a, for the Apennines earthquakes with $M \geq 5.8$ (1850-2008).

The seasonal (spring-summer) peak, is clearly visible in figs 1 and 2 and corroborates Heki's (2003) findings for Japan.

In fig. 3a and fig. 3b two counter examples, where the spring-summer peak is not visible, are shown. They represent the earthquakes with $M \geq 7.0$ recorded in the period 1900-2008, in the whole Northern hemisphere (fig. 3a), and the earthquakes in the Apennines with $M \geq 5.8$, recorded in the period 1850-2008 (fig. 3b). These two figures nicely confirm that the spring-summer peak is a specific characteristic feature of the Alps and Himalaya seismicity, while the earthquakes (both N and Σ) of the whole Northern hemisphere are distributed homogeneously throughout the year and those in the Apennines tend to concentrate in winter-autumn.

The picture is made even clearer by a recent local study of Nepal seismicity by Bollinger et al. (2007) for the period 1995–2000. During this period only relatively moderate earthquakes ($M \leq 6.3$) have been recorded and the presence of a marked reduction of the number of events (N) is observed in summer. They explain this observation as due to the stress-loading accompanying monsoon rains in the Ganges and northern India. Our findings, based both on N and Σ , show that on a much longer time series and along the whole Himalaya chain, in spite of the monsoon rains effect, there is a clear spring-summer seasonal peak in seismicity with $M \geq 7.0$. Thus the reduction of summer seismicity seems to be limited to the number N of moderate events ($M \leq 6.3$) occurring in the upper crust, whose contribution to the seismic strain release Σ is minor with respect to that of deeper, $M \geq 7.0$ crustal events modulated by the snow load.

b) Secular effect

We investigate here if size variation in time of the permanent glaciers, as mirrored by the average surface atmosphere temperature variations, influences the seismicity rate over periods of time of the centuries and we call this secular effect. The histograms of Σ and N versus time in the Alps and Himalaya and the average surface atmosphere temperature variation over the past millennium in the Northern hemisphere, expressed as index value inferred from tree-ring records (Esper et al., 2002), are reported in fig. 4.

In this section, as a counter example, we consider the Apennines, where the earthquakes catalogue is reliable for our purposes and the effect of melting of perennial glaciers, due to global warming, is negligible (Dyurgerov and Meier, 2005, GLIMS Glacier Database; World Glacier Inventory (WGI)).

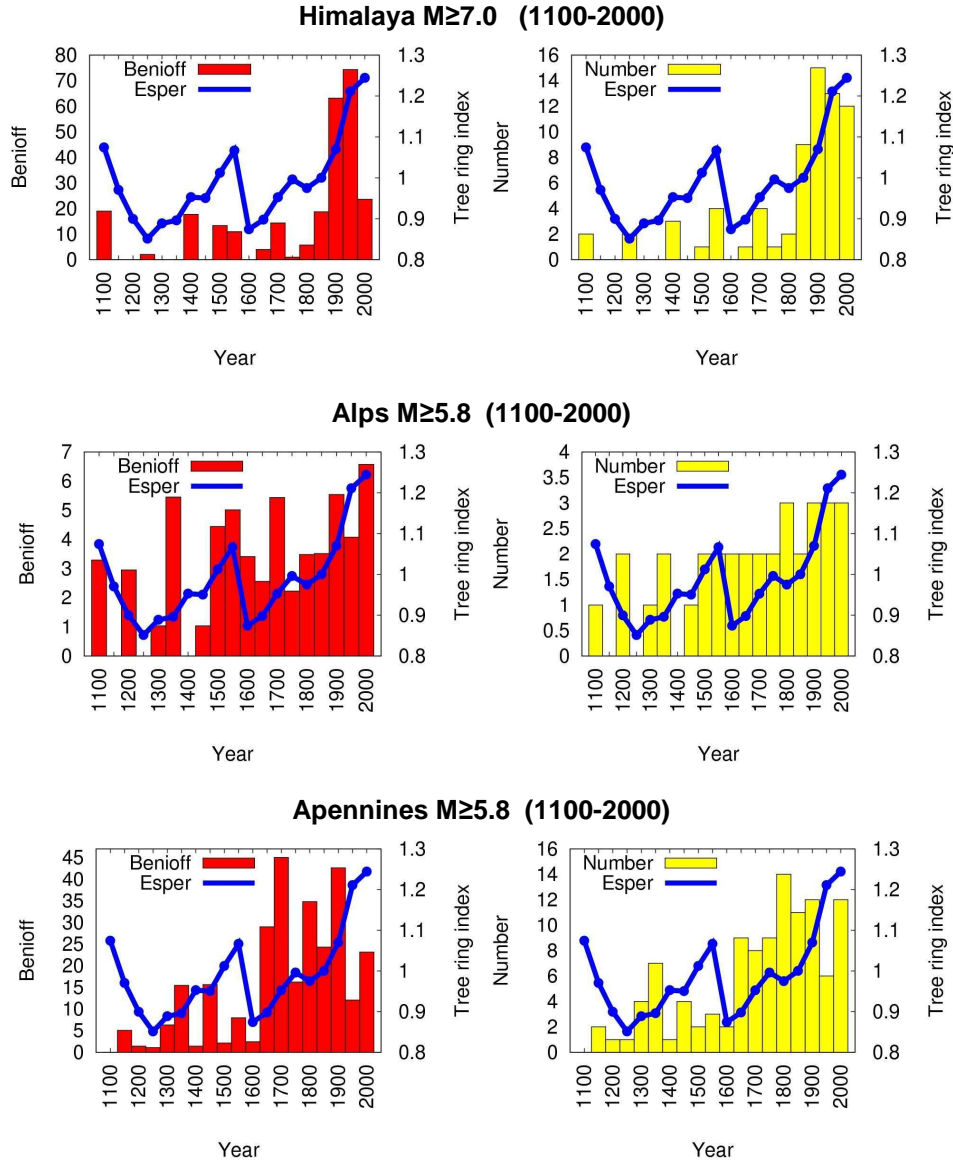


Fig. 4. Histograms showing Σ and N , in 50-year bins for the considered areas and average surface atmosphere temperature (Esper et al., 2002). The quantitative estimate of the statistical significance of the correlation between seismicity and temperature variation is given in Table 2.

The correlation between average surface atmosphere temperature (Esper et al., 2002) and seismicity, using time bins of 50 years, is computed considering Spearman's rank correlation coefficient (Spearman, 1904). It is appropriate to perform the correlation analysis considering Spearman's rank correlation coefficient, since it is a non-parametric measure of correlation – that is, it assesses how well an arbitrary function could describe the relationship between two variables, without making any assumptions about the frequency distribution of the variables. From the results summarized in Table 2 the statistical significance of the correlation between changes in average surface atmosphere temperature and seismic activity (both N and Σ) is evident in the Alps and Himalaya, while in the Apennines, where glaciacion and subsequent

glacier shrinking have been minor events in the past millennium, the correlation is certainly missing.

Table 2. Spearman correlation coefficient between seismicity (Σ and N) and average surface atmosphere temperature estimated for different time intervals. The confidence level is $\geq 95\%$ (p-value, given in parenthesis, is ≤ 0.05) in the Alps and Himalaya.

Region	Σ since 1100	N since 1100	Σ since 1500	N since 1500
Himalaya	0.79 (<0.01)	0.69 (<0.01)	0.79 (0.01)	0.78 (0.01)
Alps	0.51 (0.03)	0.49 (0.03)	0.66 (0.03)	0.60 (0.05)
Apennines	0.20 (0.41)	0.29 (0.24)	-0.14 (0.69)	0.21 (0.54)

Conclusion

The seasonal (spring-summer) peak in the seismicity recorded in the Alps and Himalaya since 1850 confirms Heki's (2003) findings for Japan, thus adds statistical significance to the spring thaw enhancement of seismicity beneath the snow cover.

The mini-glaciation from about 1350 to about 1850, well documented in the Northern hemisphere (Esper et al., 2002; Jones and Mann, 2004 and references therein; Imbrie and Imbrie, 1979), well correlates with a minimum of seismicity. Seismic activity increases very rapidly after 1850, in correspondence with the beginning of the ongoing warm period (Ward, 2009; Esper et al., 2002; Jones and Mann, 2004 and references therein).

We can thus conclude that secular variations of permanent glaciers dimensions, as well as seasonal snow load, cause crustal deformations that modulate seismicity in the major active mountain ranges in the Northern hemisphere (Alps and Himalaya).

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